OGP Progress Report
Year One
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Projects GC04-147a & GC04-147b

Title: Integrated Modeling of Snow, Soil Moisture, Groundwater, and Lake-Levels for Long Range Forecasting of Water Resources in the Great Salt Lake Basin

Project Duration: 05/01/2004 - 04/40/2007

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Introduction: This research is developing a multi-scale integrated model for water and energy in the mountain-front setting of the Wasatch-Great Salt Lake (W-GSL) system in north-central Utah. The watershed is within the Great Basin Physiographic province of the western US. The W-GSL basin is forced by snowmelt, recharge, streambed recharge, and evaporation-transpiration. The water and energy balance changes dramatically across the mountain-front. That is, mountain precipitation exceeds annual evapotranspiration $P > E$, and on the valley floor $P \approx E$. The integrated model for the Great Salt Lake Basin will utilize the new Penn State Integrated Hydrologic Model (PIHM) recently developed by Qu and Duffy (2005), with new subroutines for a 2-layer snowmelt model (Marks, 2002), and lake level-area-volume model. Signal processing tools are being developed for the purpose of detecting hydrologic change in the historical record as a first step in this project. An experimental "total-flux" array is being developed at nearby Reynolds Mountain watershed for integrated cold- and warm-season observations of local groundwater flow, infiltration-recharge, snowmelt, evaporation, and transpiration. The array was partially installed with above- and below-canopy eddy flux tower in the Fall 04.

Project Goals/Objectives: The basic hypothesis of the research is: *The water cycle within topographically and hydrologically-closed landforms of the Great Basin represent a multiscale averaging and amplification of the regional climate signal. The dominant time scales of the output (streamflow and lake level) are determined by the space-time scales of storage within the mountain and basin system. Recently identified thresholds, feedbacks and nonlinearities in mountain-front stream-aquifer-lake system serve to amplify low-frequency modes in atmospheric forcing (Duffy, 2003) causing relatively weak climate oscillations to become dominant modes within the basin through a mechanism of stochastic resonance, or noise-induced (e.g. weather) amplification.*

The research will test this hypothesis and show how natural variability of closed-basin response to climatic fluctuations from random, seasonal, interannual, interdecadal and longer oscillatory components may interact with the time scales of deep soil-moisture and groundwater storage to amplify low-frequency modes in runoff and lake levels.
Methods: The research during the first year focused on four methods central to this research effort. :

Signal Processing

During the first year of this project we have developed a method for detecting hydrologic change in the water budget across mountain fronts in the western US using spectral filtering and reconstruction of low-frequency oscillations (annual, interannual, and decadal) from historical records of precipitation, temperature, and runoff (P-T-Q). The reconstruction, based on singular spectrum analysis, removes high frequency variability and reveals the underlying patterns of the P-T-Q phase plane for a given region. The P-T-Q phase plane reconstruction for mountain-front hydrology was first introduced for the Wasatch range by Shun and Duffy (1998). The extension of this concept for detecting change has been the initial focus. These results will be extremely important to the modeling effort, since the model must be sensitive to the (sometimes) subtle changes in climate and landuse history of the region over the period of record. Details of the method and analysis have been submitted to Water Resources Research (Kumar and Duffy, 2005). Although we have not completed the analysis for the W-GSL, the Great Salt Lake spectrum in Figure 1a shows that the long record (1847-present) is rich in annual, interannual and decadal oscillations.

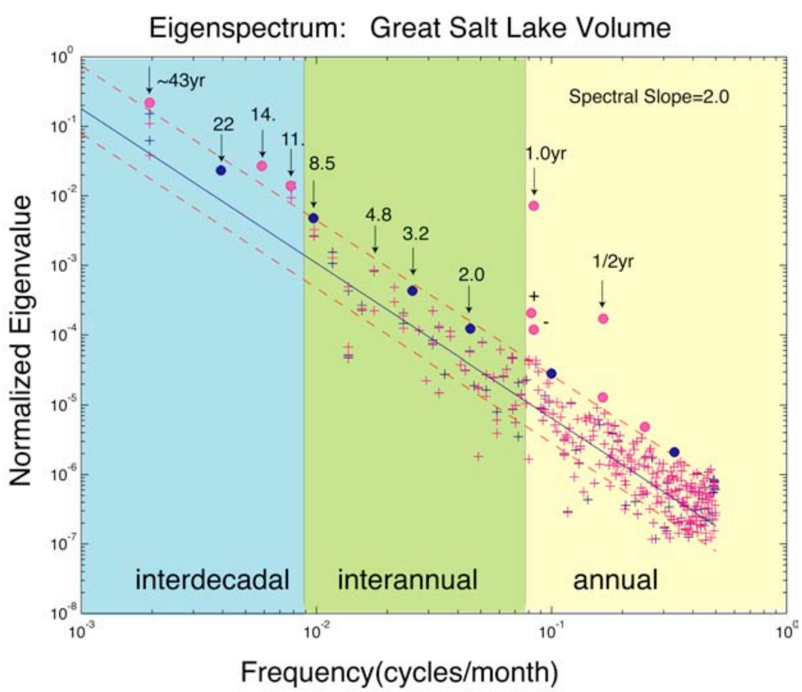

Figure 1a.The Great Salt Lake eigenspectrum estimated from the observed lake volume record 1847-1997. Note the power-law behavior of the low-frequency oscillations (spectral components with frequency $f < 0.083$ cycles/month (period >12 months).

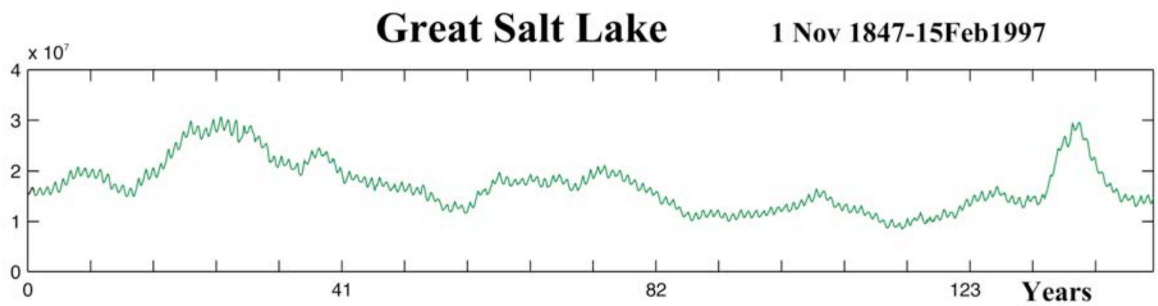

Figure 1b. The recorded time series (1847-1997) of the Great Salt Lake volume. Note the importance of long-term decadal oscillations in this case.

GIS, Remote Sensing & Snowpack Monitoring & Mapping

The estimation of snowmelt, evapotranspiration and recharge is influenced by many variables, including atmospheric conditions, terrain, land use/land cover (LULC), and hydraulic properties of the underlying soils and geology. The modeling strategy relies on GIS data layers for all inputs to the integrated model including: delineation of watershed boundaries and/or model hydraulic boundaries, recharge patterns, topography, soils, geology, water table, depth of active flow, aquifer properties, etc. Our approach is to form a multi-scale dynamic water budget using an approximation to the fully-coupled equations of motion for surface and subsurface flow forced by atmospheric inputs and snowmelt. Details of the integrated model are described in a later section. Table 1 is listing of the necessary model data sets and the coarse-resolution GIS database currently acquired for the W-GSL watershed. This database will support the initial modeling activity to begin in year 2 of the study. The low-resolution model will be our first implementation of the integrated model and will provide initial estimates of snowmelt and recharge across the basin and initial conditions for high-resolution simulations for year 3.

Validation sites have been established within the USDA-ARS Reynolds Creek Experimental Watershed. A small snow-dominated headwater catchment (0.4 km^2, 2024 – 2139 m) has been instrumented for detailed monitoring of snow thermal and mass, soil moisture, groundwater and streamflow conditions, including 9 micro-meteorological stations, 4 snow energy balance EB sites, and an ETRS system. A larger catchment (1.8 km^2, 1488-1868 m) located within the rain-snow transition zone, spans a greater elevation range. It is instrumented with three primary micrometeorological stations (top, mid, and base) with a connecting transect of temperature and humidity measurement sites allowing us to collect detailed measurements on how moisture and temperature lapses within the Great Basin region. These two intensely instrumented catchments will provide information for scaling processes and precipitation form and distribution using a combination of station and remote sensing data from the detailed catchment scale to larger areas within the Great Basin.

Category	Data Sets	Type	Characteristics
Climate	P, T_{min}, T_{max}	Point	Monthly; 1/24° grid; 1895-2004
	SR, SR_i, RH, P_{vap}	Point	Monthly, daily ; 1/2° grid; 1895-1993
	PET, AET, W	Point	Monthly, daily ; 1/2° grid; 1895-1993
Vegetation	VGVT, LAI, LAIW	Point	Monthly; 1/2° grid; 1895-1993
Topography	z_{gs}	Grid	Grid; 1 arc second
Streams	Name, HUC, FlowDir, P/E	Line	1:100,000 scale
	Name, Q, DA, W, D	Point	Spatially distributed; hourly-daily
	ID, FlowDir, Order, DA	Line	Grid; 1 arc second; calculated from topography grid
Waterbodies	Name, HUC	Polygon	1:100,000 scale
Reservoirs	Name, SA, DA, SV_{norm}, SV_{max}	Point	Spatially distributed; 1:2,000,000 scale
Soil	Name, PermH, PermL, RockDepH, RockDepL	Polygon	1:250,000 scale
Physiography	Province, Age, Section, Glaciation	Polygon	1:100,000 scale
Hydrogeology	FM, Age, RockTyp	Polygon	1:250,000 scale
	FM, Section, K_{sat}, D, n_p	Table	Compiled measurements
Wells	ID, Alt, Levels	Point	Spatially distributed; Compiled measurements
Conceptual model	All of the above.	Figures, Tables, Text	Compiled summaries, concepts, and measurements

Table 1: This table lists the preliminary GIS data/parameters for the Wasatch-Great Salt Lake basin to be used for the low-resolution model. Year 2 will see extensions to this database with higher resolution as available.

Integrated Modeling

A third area has been continued development of our new integrated hydrologic model PIHM. Our present work involves the implementation of a 2-layer snow model along the lines of Marks (2002), a GIS interface, and planning for a parallel version of PIHM for cluster computing to be carried out in years 2-3. More details are given in the **Results** section.

ETRS Array

A fourth method involves the design and installation of a total-flux array for testing the concept of an integrated flux measurements. We refer to this as an ETRS array (e̲vaporation-t̲ranspiration-r̲echarge-s̲nowmelt). Using this experimental setup we are attempting to get a comprehensive evaluation of the relation of snowmelt to recharge and runoff, while at the same time observing the atmospheric and energy and moisture fluxes. The array will allow a comprehensive and coherent set of flux observations of the atmosphere-land surface (snow and vegetation)-subsurface system at a highly monitored site. The experimental setup is discussed in **Results** below.

Results and Accomplishments

Signal Processing

Figure 2 (Kumar and Duffy, 2005) gives six examples of P-T-Q reconstruction of low-frequency oscillations (annual, interannual, and decadal) within the Colorado Plateau and Rocky Mountain regions. Average annual oscillations are shown for the first half of the 20th century (pre-1950) and the second half (post 1950). Significant hydrologic changes are observed in each case. The orange trajectory is the pre-1950 annual average and the blue is post-1950. Also shown are the January, May and August point P-T-Q data for each period, indicating how the monthly data has varied over the 20th century. In most cases the significant hydrologic change that has occurred is not a change in the P-T-Q pattern, but a significant reduction in the runoff (vertical axis) due to human activity. More subtle effects are seen in the Tombstone example where winter precipitation has increased in the late 20th century and a clear climate change impact.

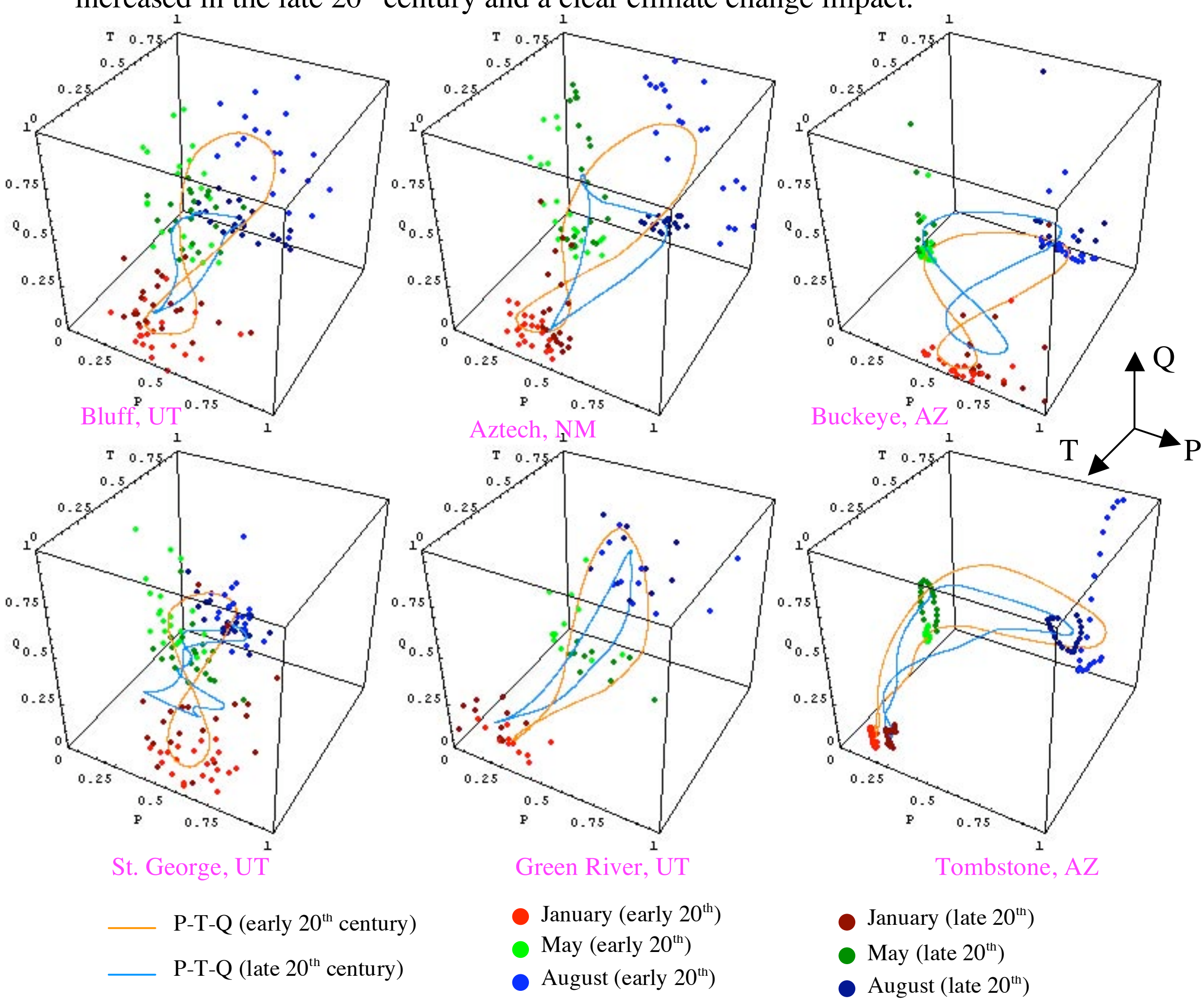

Figure 2. P-T-Q phase-plane trajectory plot for low frequency (annual, interannual and decadal) reconstructed time records showing how the phase-plane has changed from early-to-late 20th century. Q-vertical and, P-T on the horizontal axes.

Process	Governing equation	Original governing equations	Semi-discrete form	Approximation
Channel Routing	St. Venant Equation	$\frac{\partial h}{\partial t}+\frac{\partial(uh)}{\partial x}=q$	$\left(\frac{d\varsigma}{dt}=P_c-\sum Q_{gc}+\sum Q_{oc}+Q_{in}-Q_{out}-E_c\right)_i$	Kinematic or Diffusion wave
Overland Flow	St. Venant Equation	$\frac{\partial h}{\partial t}+\frac{\partial(uh)}{\partial x}+\frac{\partial(vh)}{\partial y}=q$	$\left(\frac{\partial h}{\partial t}=P_o-I-E_o-Q_{oc}+\sum_{j=1}^{3}Q_s^{ij}\right)_i$	Kinematic or Diffusion wave
Unsaturated Flow	Richards' Equation	$C(\psi)\frac{\partial\psi}{\partial t}=\nabla\cdot(K(\psi)\nabla(\psi+Z)$	$\left(\frac{d\xi}{dt}=I-q^0-ET_s\right)_i$	Shallow water table
Groundwater Flow	Richards' Equation	$C(\psi)\frac{\partial\psi}{\partial t}=\nabla\cdot(K(\psi)\nabla(\psi+Z)$	$\left(\frac{d\zeta}{dt}=q^0+\sum_{j=1}^{3}Q_g^{ij}-Q_t+Q_{gc}\right)_i$	2-D Dupuit approximation
Interception	Bucket Model	$\frac{dS_I}{dt}=P-E_I-P_o$	$\left(\frac{dS_I}{dt}=P-E_I-P_o\right)_i$	N/A
Snowmelt	Temp Index Model	$\frac{dS_{snow}}{dt}=P-E_{snow}-\Delta w$	$\left(\frac{dS_{snow}}{dt}=P-E_{snow}-\Delta w\right)_i$	N/A
Evapotran-spiration	Pennman-Monteith Method	$ET_0=\frac{\Delta(R_n-G)+\rho_a C_p\frac{(e_s-e_a)}{r_a}}{\Delta+\gamma(1+\frac{r_s}{r_a})}$	$\left(ET_0=\frac{\Delta(R_n-G)+\rho_a C_p\frac{(e_s-e_a)}{r_a}}{\Delta+\gamma(1+\frac{r_s}{r_a})}\right)_i$	N/A

Table 2. Major hydrologic process, governing equations, and approximation for PIHM.

Integrated Modeling

This research is implementing an integrated finite volume model for simulating dynamic/distributed water budget including the estimation of distributed snowmelt, evapotranspiration, recharge, surface runoff, and baseflow. The model is known as PIHM (Penn State Integrated Hydrologic Model) and includes overland flow, unsaturated flow, groundwater flow and channel flow processes (Table 2). The model also includes algorithms for snowmelt and vegetation water use. However, both of these will be improved in this study. PIHM is utilized in this application as a multi-scale, distributed-dynamic water budget for groundwater and surface water in the GSL basin. Table 2 shows the processes, and the original and reduced governing equations. For channel routing and overland flow the kinematic wave and/or diffusion wave approximation will be used. For saturated flow, the 2-D Dupuit approximation is applied. For unsaturated flow a 1-D vertical integrated form of Richards's equation is applied.

The watershed domain decomposition applies Delaunay Triangulation with constraints in 2-D and project it to prisms, as shown in Figure 3. The advantage is that the flux across any edge to its neighbor is always normal to its common boundary by definition. This reduces computational cost to evaluate flux across element boundary. The scope and scale of water resource problems make GIS a powerful tool in developing solutions (Maidment, 2002). In PIHM, geographic information system (GIS) tools are used for domain decomposition, data analysis, pre- and post-processing of data parameters visualization. The unstructured grid used to decompose the domain is referred as triangular irregular network. The TIN is the most efficient way to represent the terrain and meet simulation goals for computational efficiency, constraints on hydrographic points (including hydraulic structure, such as gage stations and dams) or critical terrain points (including local surface maximum/minimum, convexity/concavity, or saddle points), and these are easily accomplished in the GIS tool.

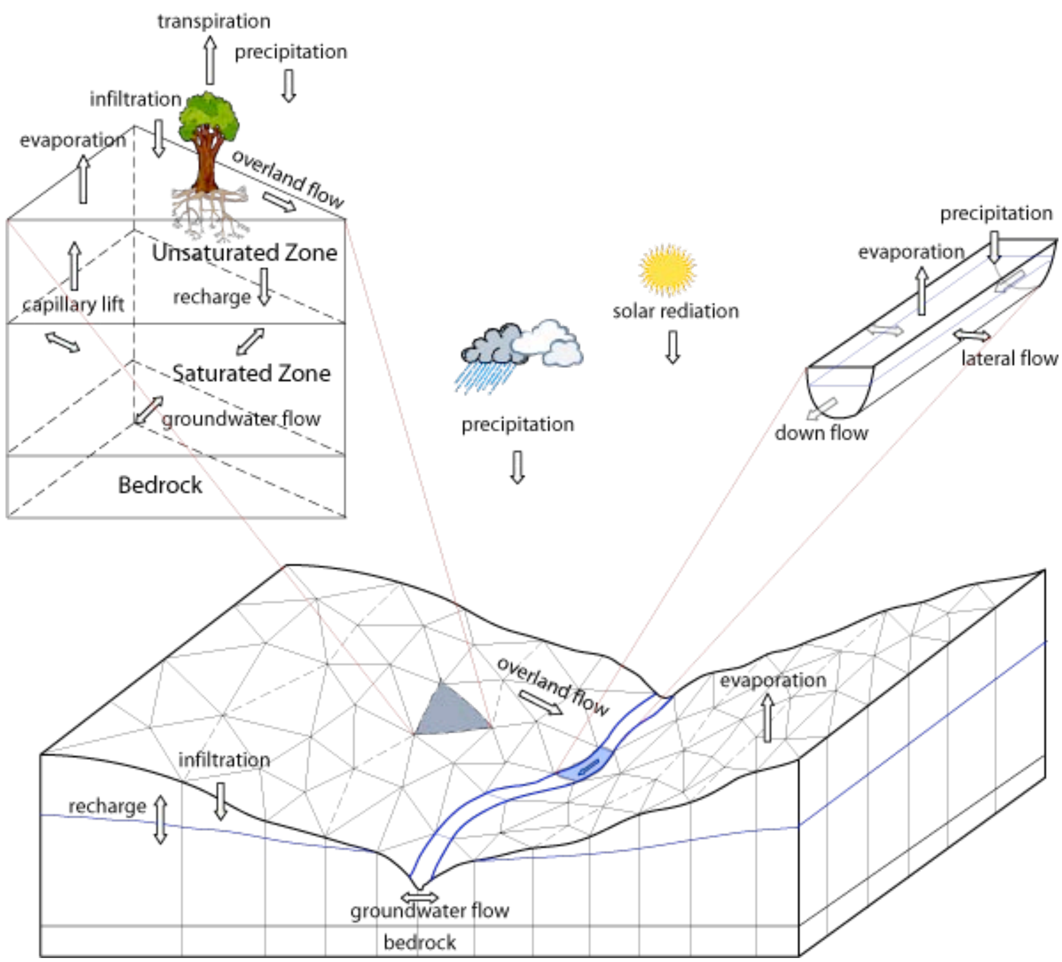

Figure 3 The domain decomposition for PIHM within a stream reach. Each prism element incorporates the multiple hydrological processes listed in Table 2. A channel segment is shown to the right.

Evaporation-Transpiration-Recharge-Snowmelt (ETRS) ARRAY

The use of meteorological flux towers and eddy covariance systems in mountainous regions to estimate evapotranspiration (ET) is complicated by the variable footprint of the observations, where wind speed, wind direction, turbulence and the surrounding terrain, affect the scale of the moisture-flux estimate. This is further complicated for cold season conditions when evaporation from the snowpack occurs under stable atmospheric conditions. For patch-scale research or topographic transects where differences in water use by vegetation type is critical, the impact of the changing atmospheric footprint on estimates of ET is not well understood.

This element of our research involves the development of a new theory and experimental design for the total moisture flux estimation suitable for warm and cold season conditions. The experimental array is located within a fixed, finite volume of soil using concurrent soil moisture, water table, and meteorological sensors. The experimental design requires soil moisture and water table sensor arrays to be deployed at the centroid and boundaries of the soil volume, with precipitation measurements and eddy flux tower positioned centrally within the array. For the model, a local, dynamic water balance is formed by direct integration of Richards equation using a Finite Volume (FV) formulation of unsaturated-saturated moisture storage. The resulting dynamical system is continuous in time, discrete in space. Using field estimates of soil characteristic curves, the dynamical equations are solved numerically. The experiment will show how the theory can be used for optimal sensor design given soil conditions and the optimal estimation of the total flux components within the array. We refer to the total flux measurement system as an ETRS array (Evaporation, Transpiration, Recharge, and Snowmelt).

During the fall 04 we installed an ETRS array at the Northwest Watershed Research Center, near Boise. The instrumentation package included: eddy flux towers at 2 heights above and below the canopy; snow depth, density, radiation, temperature instrumentation; soil moisture, temperature and soil potential at 3 depths above the water table; an equilateral or finite element array of piezometers with pressure tranducers to estimate the lateral flux of groundwater to the adjacent stream.

The complete measurement suite will be particularly important during periods of very stable winter air masses which can invalidate the eddy-flux estimate, and making alternative flux estimates important for reducing errors from the instruments. During the warm season the ETRS array will allow independent estimation of evaporation and transpiration. We expect to be able to using redundant or multiple flux estimates for improving or reducing the uncertainty in the evaporative flux within the array. Groundwater level observations will allow recharge and the lateral flux of groundwater to estimated within the same finite volume of soil.

Figure 3. Eddy-flux tower at the Northwest Experimental Watershed, USDA.

Future Work:

The year 2 investigation will begin development of a spatially-distributed water budget (recharge, evapotranspiration, baseflow, surface runoff, snowmelt) for the low resolution model. We will make use of updated land cover maps, long-term national climatic database products for low-resolution climatic data for the observation record. The investigation will use existing digital GIS hydrogeologic, physiographic, climatic and landuse data to support the model development. Simple optimization tools will be used in the watershed calibration step to improve on the a-priori model parameters. In year 2 we will also focus on additional data sets from instrument record (1895-2005), NCEP Reanalysis data (1948-2003), the NCEP Regional Reanalysis data (1975-2003), and higher resolution soils, vegetation, and geologic data in our GIS coverages. The first product of this research is a multi-resolution basin-scale reconstruction of closed-lake level fluctuations, soil moisture, groundwater levels and streamflow over a 25 and 50 years period. The second product will be analysis of the NCEP/LDAS products as forcing for long range water resource forecasting.

Publications from this project:

<u>Journal Publications</u>

Garen, D. C. and **D. Marks**, 2005. Spatially distributed energy balance snowmelt modelling in a mountainous river basin: Estimation of inputs and verification of model results, *Journal of Hydrology* (in press).

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